Subsurface Conditions Promoting Groundwater Contamination At Elkhart, Indiana

Undergraduate Research Thesis

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By

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ABSTRACT

This study investigated multiple plumes of chlorinated solvents in groundwater at Elkhart, Indiana in relation to the subsurface lithology, the geologic history of the area, and key factors controlling the migration of contaminants. The aim of this study was to understand seminal events promoting the development of these extensive contamination plumes within the study region. This was done through the analysis of literature surveys along with the examination and interpretation of a collection of gamma-ray logs available from Indiana Geological Survey. The logs covered much of the area affected by the variety of large contaminant plumes. The shallow geology proved to be a complex mosaic of glacial outwash and other interbedded glacial deposits. Across the study area, little to no distinct pattern of layering was indicated by the gamma-ray logs. The unconfined, permeable aquifer beneath Elkhart connected the near-surface chemical disposal sites and promoted the rapid infiltration of precipitation and the growth of contaminant plumes in the groundwater. The St. Joseph River close in proximity to the disposal sites contributed a steep hydraulic gradient, which propagated this rapid expansion. The porous, permeable, and varied subsurface setting, coupled with the previous lack in disposal regulations advanced the development of significant contaminant plumes. The most seriously contaminated sites are currently being remediated.

Acknowledgements

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Introduction

The objective of this study was to investigate the subsurface stratigraphy of Elkhart, Indiana and connect these findings to the groundwater contamination that is found in the area. The primary mode of information gathering for this project was literature collection and analysis about the study area to gather information on the groundwater contamination and public health effects. A secondary mode of data analysis for this research required the collection of gamma-ray bore logs and sediment bore logs provided by the Indiana Geological Survey. By reconstructing sediment bore logs and comparing that with the information about sediment size provided by gamma-ray evidence, cross-sections of the study area were created.

The study area contains a portion of the city of Elkhart, Indiana. Beneath Elkhart lies an expansive, thick unit of glacial outwash deposits. Largely sand and gravel, these deposits create an ideal aquifer system. The heterogeneous composition of the glacial deposits has been classified by some into three distinct units. The high susceptibility to contamination arises from the unconfined nature of the Upper Aquifer unit. Overlying this aquifer is the Conrail Railyard and portions of the St. Joseph River (Figure 1). The four contamination plumes named by their origins that were researched in this study were the Conrail Railyard, Lusher Avenue, LaRue, and Gemeinhardt plumes. All four plumes are related to the industrialization of Elkhart, and they all contain organic, metal cleaning solvents.

Background and Physical Setting

Description of Study Area in Northeastern Indiana

The study location covers an area of 52 km^2 in and around Elkhart, Indiana (Figure 1). It includes the southern portion of the City of Elkhart and surrounding industrial and agricultural areas. The study area, more generally, is located in northeastern Indiana near the Indiana-Michigan state border. It is a region shaped by Pleistocene glaciations and Holocene fluvial processes. The elevation is 720 masl with relief of 15 m and uplands defined by systems of recessional glacial moraines and lowlands evident along river valleys (Arihood et al., 1998).

Figure 1. Map of the study area in Elkhart, Indiana including the St. Joseph River and other landmarks. Wells of Interest mapped through ArcGIS and represent the location of gamma-ray logs analyzed. Image through GoogleEarth Pro.

The region is drained by the St. Joseph River within a basin of ~2820 km^2, which is located in northern Indiana and southern Michigan (Figure 2). Within the study area, the most important tributary to the main stem of the St. Joseph River is the Elkhart River, which drains upland areas of Elkhart, Noble and Kosciusko Counties.

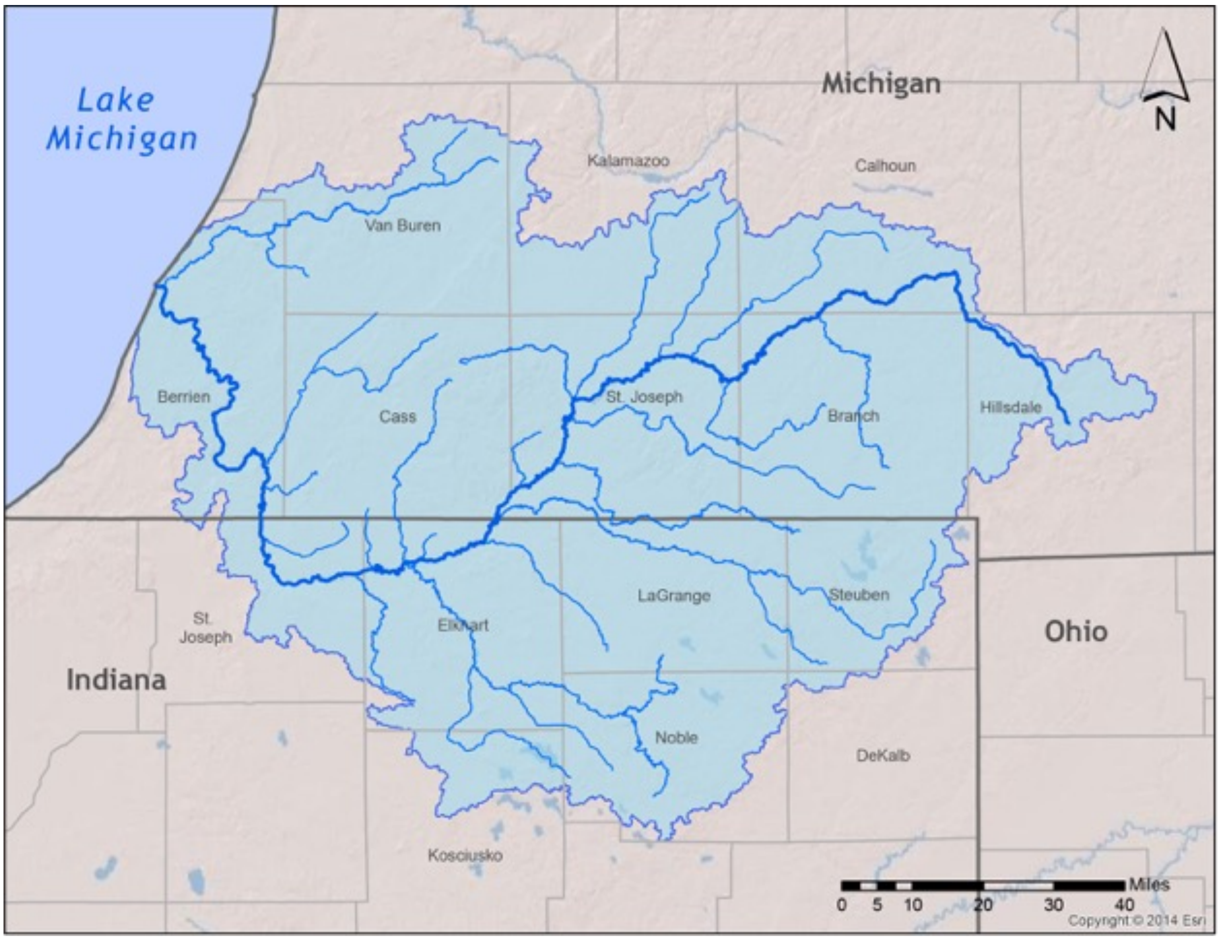

Figure 2. Map of the St. Joseph River Basin in Michigan and Indiana. (From http://www.sjrbc.com/)

The uppermost bedrock in northeastern Indiana includes Paleozoic-age carbonate, siltstone, and shale rocks (Beaty and Clendenon, 1987). In the local study area location, the uppermost bedrock layer is primarily shale. These are generally considered to be poorly permeable units with low groundwater yields. The basement rock throughout northeastern Indiana is igneous rock from the Precambrian Era. Bedrock is mantled by glacial deposits that are generally about 45 m (Beaty and Clendenon, 1987). The relatively thick glacial layer of glacial deposits is due to glacial retreat during the Wisconsin deglaciation event. Deposits consist mostly of glacial till and outwash. Across the area, the outwash deposits are important aquifers (Fenelon et al., 1995). The aquifers provide a large source of water for the study area. Locally, industrial and municipal wells can yield upwards of 64 million L/day with about 50% of the withdraw being accounted for by the City of Elkhart (Arihood et al., 1998). The aquifers are vital to the longevity of the city.

Climate

The average air temperature in the area from 1991 to 2010 was around 10ºC with an average annual precipitation of 99 cm over this time period (Wang et al., 2017). This temperate continental climate indicative of the US-Midwest has been generally consistent. Over the area of the basin, high daily temperature variability is common. Precipitation is generally consistent throughout the year, and the climate is influenced by the proximity of Lake Michigan. The region experiences moderate winds from the southwest, and is characterized by high humidity (Beaty and Clendenon, 1987). Along with humidity and wind, the monthly precipitation and temperature (*Table 1*) have implications for the water supply for the study area. The highest precipitation occurs during the months of May, June, and July.

The highest temperatures occur during the summer months of June, July, and August. During the high precipitation months, the water supply for the study area is relatively more affected than the low precipitation months. Overall, the precipitation nearly doubles from the February low of 5.2 cm to the July maximum of 10.8 cm. The change in average temperature is at 27 ºC from winter lows to summer highs (Table 1). This is common for the seasonality experienced in the Midwestern United States.

Table 1. Normal temperature and precipitation monthly values from 1981 to 2010. Data collected from the National Weather Service (NWS). Normal values as determined by the NWS.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Temperature (ºC)	-3.9	-2.1	3.6	10.0	15.8	21.2	23.1	21.9	17.9	11.4	5.2	-1.6
Precipitation (cm)	5.7	5.2	6.9	8.9	10.8	10.6	10.8	9.2	7.1	7.2	7.8	7.0

Land Use

Over the St. Joseph River Basin, the land coverage varies between urbanized areas, farmlands, and forest and woodlands. This entire basin contains 4.7 percent of the total land area in Indiana, and the most intensive development through industry and residential means is near the cities of South Bend and Elkhart (Beaty and Clendenon, 1987). During the industrialization boom in the early 1950s, Elkhart, Indiana became blanketed with impervious surfaces.

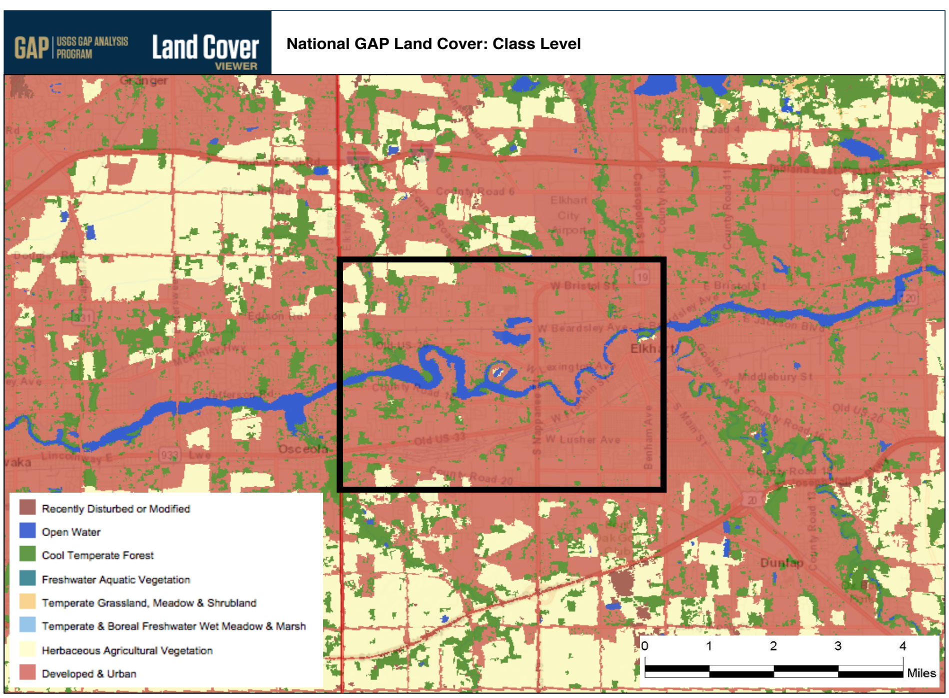

Figure 3. Land Cover Map showing the land usage in Elkhart County, Indiana. Study area is outlined in black. Map and data taken from the USGS.

From the addition of traveling trailer and woodwind businesses to a railyard, Elkhart has become one of the most industrialized cities in the St. Joseph Basin. The entire state of Indiana is classified by the United States Geological Survey (USGS) herbaceous agricultural vegetation, but this is not the case in the city of Elkhart. As shown in Figure 3, the land cover of Elkhart Indiana–encompassing the study area–is largely classified by the USGS as developed and urban area. The estimated amounts of land cover in the study area are as follows: 5 percent herbaceous agricultural vegetation, 8 percent cool temperate forest, 10 percent open water, and the remaining 77 percent developed and urban. By Elkhart being mostly urbanized, the transfer of water between the surface and subsurface as well as the flow of water in these locations is affected.

Elkhart Indiana

The city of Elkhart is home to about 52,000 people currently and covers a land area of about 78 km^2. It resides in Elkhart County near the border between Michigan and Indiana.

Figure 4: Wellfield Botanic Gardens in Elkhart, Indiana. Picture courtesy of amishcountry.org

Northern Indiana in general was originally inhabited by several Native American tribes. The names of these tribes have been used to identify the rivers, lakes, and towns as a reminder of the area's history (Glen, 1997). The county of Elkhart itself was one of the first counties to be settled and established in the northern Indiana region during an act of Legislature in 1830 (History of Our Communities, 2018). Since then, the county has grown and flourished in the areas of travel and industry. The county still holds traditional values, and it is a mix of contemporary industry and Amish culture. This area is currently well-known for its key role in the automobile and recreational vehicle industry. The city of Elkhart contributes greatly to the industrialization that has characterized Elkhart County.

The city of Elkhart resides on the convergence of the Elkhart and St Joseph Rivers. The proximity to the rivers and to large cities such as Fort Wayne, Indiana and Chicago, Illinois prompted growth of Elkhart. The city has been known for its industrial roots. With the addition of Schult producing traveling trailers in the mid-1930s, Elkhart was on its way to becoming the "RV Capital" of the world (History of Our Communities, 2018). Conrail Railyard, a functioning railyard just outside of downtown Elkhart, began its operation in 1956 (ATSDR, 2005). The proximity to Chicago, Illinois made this city a premier location for a classification rail yard which has since become very popular. Each day, about 74 trains are processed on the classification tracks, and the engines are repaired, and the rail cars cleaned (ATSDR, 2005). Along with the mobile home industry and the rail yard addition, Elkhart also was also introduced to the music industry, as woodwind companies joined in the prosperous business environment.

All of this industry called for the use of metal cleaning solvents. From the mid-1950s to 1980, large quantities of used metal cleaning solvents were disposed of improperly through on-site dumping. These activities, particularly south of the St. Joseph River, led to severe contamination of the unconfined sand aquifer occurring there. The ramifications of resulting chemical exposure to groundwater users are generally unknown.

Figure 5: (Top) Conrail Rail Yard in Elkhart, Indiana. (Bottom) Grand Design RV Company in Elkhart, Indiana. Pictures courtesy of www.american-rails.com/conrail.html and amishcountry.org, respectively.

Retreating Glaciers: A Conceptual Model

Continental glaciers are well-known for ability to modify landscapes through various kinds of erosion. Glacial processes are also important in creating distinct landforms and in depositing various types of unlithified sediments. Diamictons form in association with advancing glaciers with these poorly sorted materials transported and deposited at base of the ice. These unlithified materials are commonly unsorted with grainsizes of particles ranging from clay to boulder size.

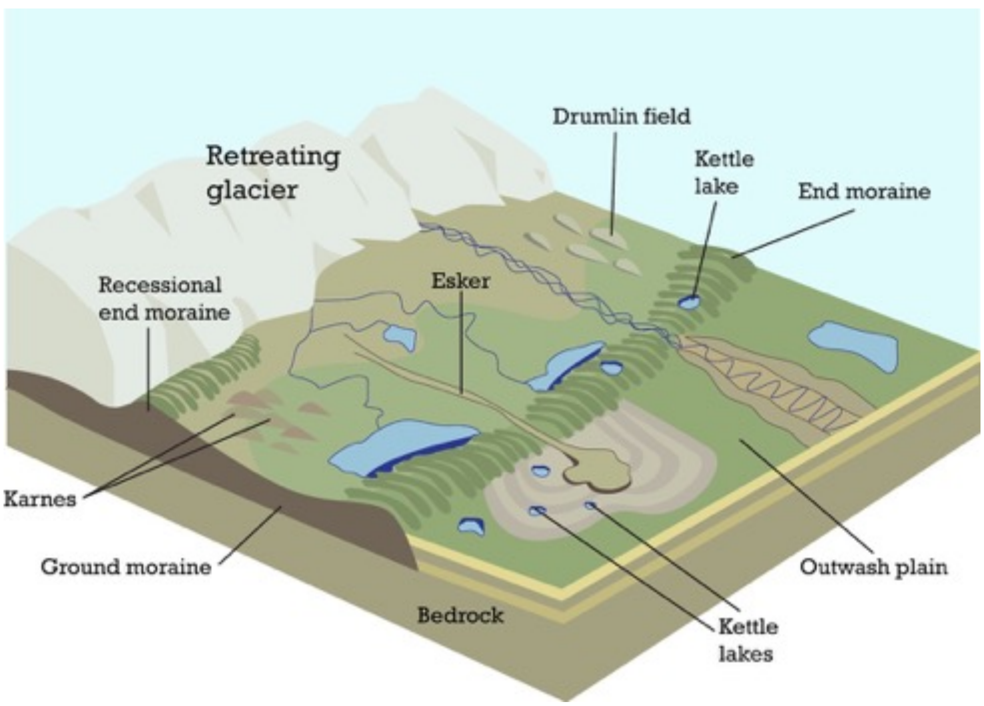

Figure 6. Diagramtic model of glacier retreat. All landforms created by retreat are labeled. Model provided by www.ccin.ca/home

Once ice begins to melt with the glacial retreat, these materials and those entrained in the ice are exposed, commonly water washed and transported ahead of the ice to form sand and gravel outwash plains. Figure 6 is a conceptual model of deposits associated with an ice-front.

Depicted in the figure is are the glacial sediments and landforms resulting from the melting of glaciers. In particular, end moraines form when the ice front remains in one place for a time. The diamicton is sheared up all along the ice front to form a distinct line of hills. As will become clear, remnant systems of moraines across northeastern Indiana and Michigan describe the patterns in glacial retreat.

Other deposits are associated with glacial retreat. For example, if rivers are unable to drain water and transport sediments away from the ice-front, glacial lakes may also form. Another type of landform called an esker is created by rivers flowing within or on top of stagnating ice. As the ice melts, the sand and gravel sediments associated with the river melt are deposited as the ice melts to create a long narrow sand and gravel hill. Of these landforms, two most relevant to the study area at Elkhart Indiana are moraines and outwash plains.

Process Contributing to Formation of Key Units

During the Last Glacial Maximum, the Laurentide Ice Sheet covered a large portion of Canadian Shield and the northern region of the United States. The glacial processes associated with this Wisconsin ice, the last of the major Pleistocene advances, greatly shanged the land surface through erosion and deposition processes, the results of which can be seen today.

The pre-existing topography for example the Lake Michigan and Lake Erie basins produced ice lobes, e.g., the Lake Michigan Lobe (LML), the Saginaw Lobe (SL), and the Huron-Erie Lobe (HEL). These lobes marked the axes along which the ice advanced to cover the State of Michigan and the northern two thirds of Indiana.

According to Fisher and Taylor (2002), the differential rates of melting of the three glacial lobes were significant in the formation of the characteristic unconsolidated mosaic of glacial deposits in the study region of Elkhart, Indiana. At the time melting uncovered the land surface in the vicinity of present-day Elkhart the three lobes were in the same general area. The LML was present on the west-most border of Michigan in an area that corresponds to the present location of Lake Michigan today. The SL overlaid a central portion of Michigan and extended southwest to what is now the Indiana and Illinois state border. On the east-most border of Michigan, the HEL stretched southwest into current day Indiana, south of the region of interest. Because of the presence of the lake basins and the greater ice thicknesses, ice in LML and HEL was much slower to retreat than the SL. In other words, the ice front of SL retreated at a faster rate than the surrounding lobes. The result was the development of a broad channel between the LML and HEL (Figure 7).This channel carried meltwater from all three lobes west-southwest and led to the formation of the outwash in the vicinity of Elkhart that formed the main aquifer system there.

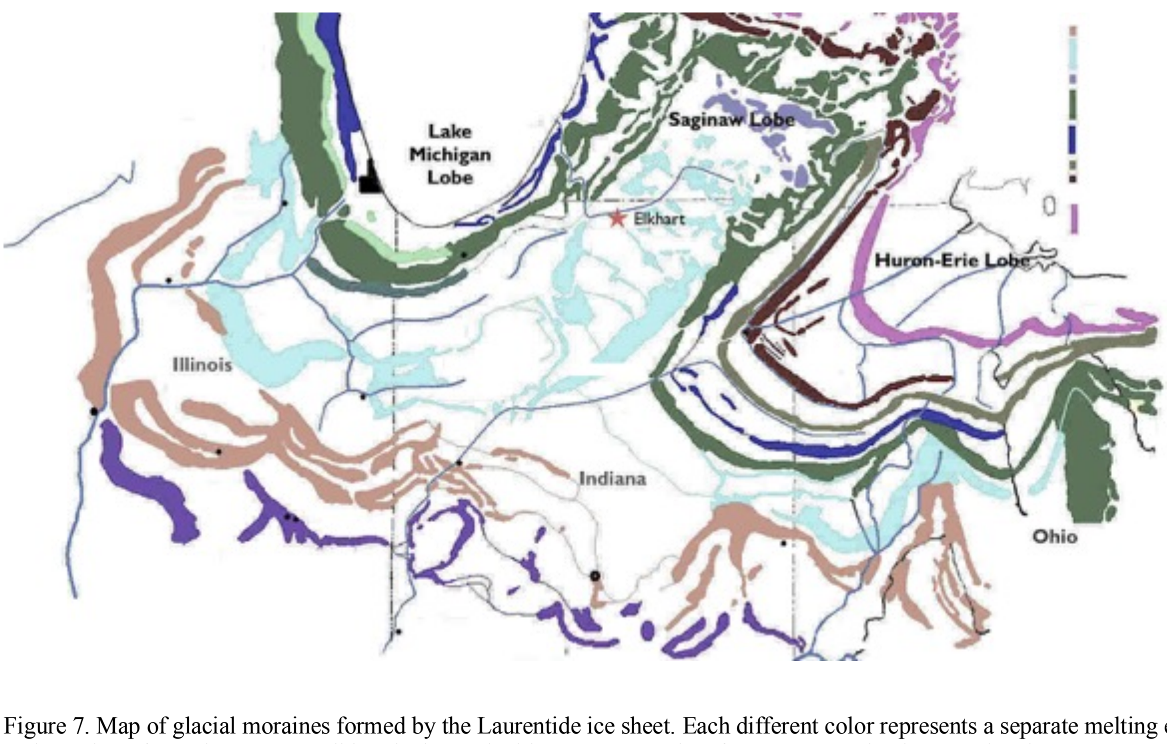

Figure 7. Map of glacial moraines formed by the Laurentide ice sheet. Each different color represents a separate melting episode and creation of moraine system. Elkhart is denoted with a star. Map taken from www.academic.emporia.edu

Figure 7 shows the end moraines associated with all three lobes. Deposition during glacial retreat resulted in moraines scattered along the horizon of current day Michigan. Multiple melting episodes occurred, leaving a multitude of moraine systems. Large volumes of glacial meltwater released during the multiple sessions of retreat are likely responsible for the thick amount of unconsolidated material deposited on top of the bedrock in the study region of Elkhart, Indiana—about 150 feet thick (Beaty and Clendenon, 1987). Unconsolidated material in this abundance produces thriving aquifers with large capacities for liquid containment and flow. Besides the outwash deposited by meltwaters moving away from the ice fronts, there were some other interesting dynamics at work.

The funneling of meltwater through the channel created by retreating lobes and damming by deposition led to the formation of glacial lakes further south than northern Indiana. The moraines and the previously established topography acted as natural dams to glacial meltwater. The immense amount of glacial meltwater contributed to a catastrophic flooding event south of Elkhart and the study area. This phenomenon was not rare during the last deglaciation event. A particularly large flooding of this nature occurred in 19,000 cal yr BP during the Wisconsin Deglaciation (Curry et al., 2014). Meltwater from the three retreating lobes deposited unconsolidated outwash across southern Michigan and northern Indiana, and it pooled in the current day Kankakee River Basin. The water became heavy behind the natural dams that it broke through the barriers to cause movement of a large slug of water. This event was named the Kankakee Torrent for its vicinity and attribution to the local topography of Kankakee, Illinois. The Kankakee torrent is responsible for forming the current day topography of northeast portion of Illinois.

Hydrostratigraphy

Glaciation of Northern Indiana has resulted in a broad array of unlithified sediment over bedrock. One of the most important units in terms of this study is the broad outwash plain in and around the city of Elkhart. Previous studies by the USGS subdivided the outwash into three units: the Upper Aquifer, the Lower Aquifer, and the Confining Unit between the two aquifers (Figure 8). In the study area, the Upper Aquifer is completely unconfined. The top aquifer unit largely consists of sand and gravel and averages 14 m in thickness with a range of 0 to 35 m (Arihood et al., 1998). This layer is generally laterally expansive, and it contains lenses of fine silt and clay. Low permeable lenses such as these may affect the flow of groundwater, but they do so only slightly. Their size renders them nearly insignificant in the overall direction and speed of groundwater flow.

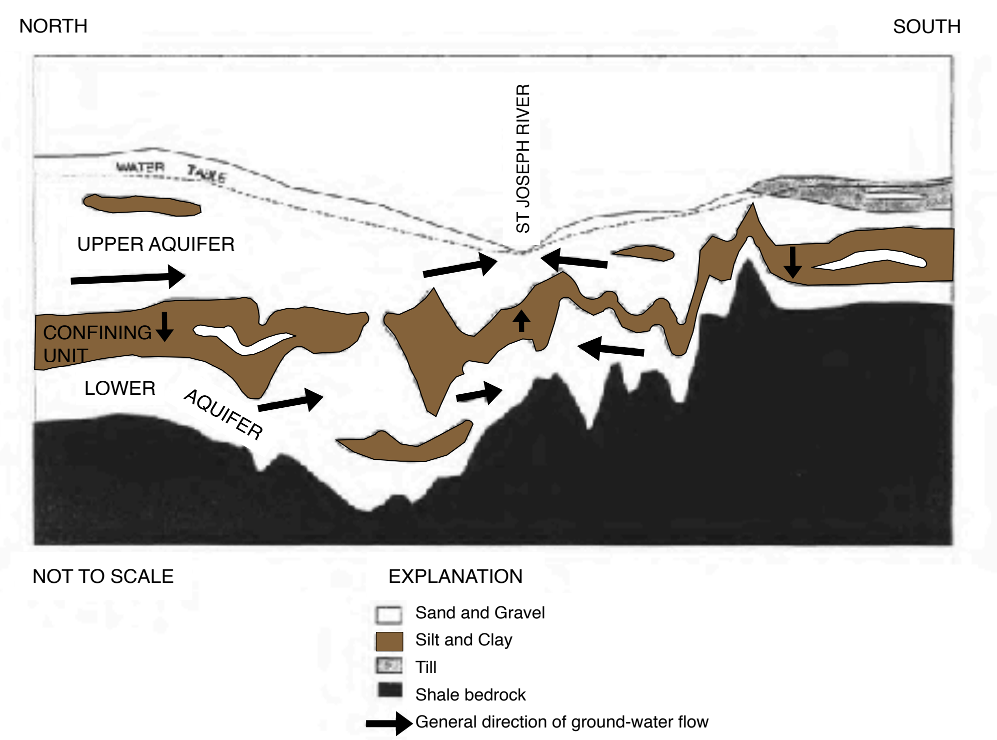

Figure 8. Cross-section provided by the USGS across an area more expansive than the study area. Shows major hydrostratigraphic units and the direction of groundwater flow(Arihood et al., 1998).

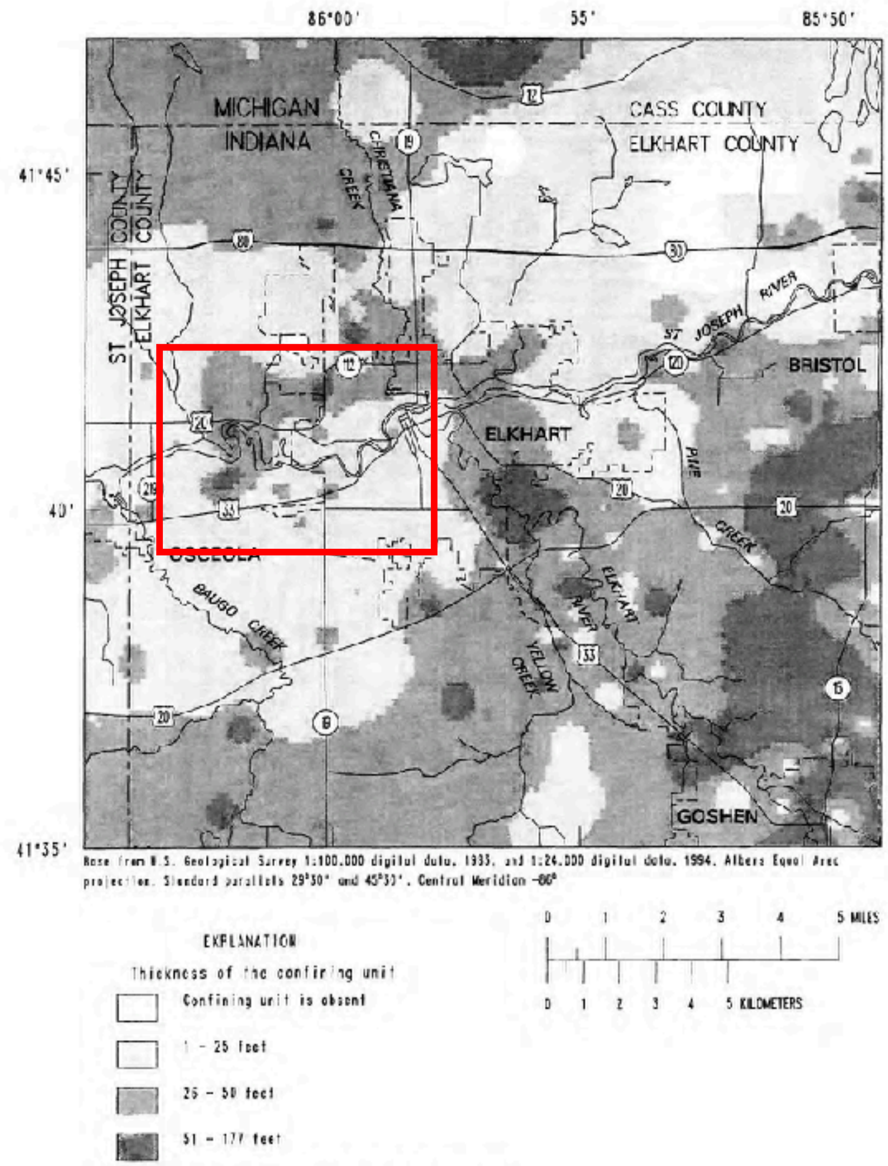

Figure 9. Thickness map of the confining layer taken from the USGS. Study Area is boxed in red.

Between the Upper Aquifer and the Lower Aquifer below lies an expansive confining unit. The Confining Unit is composed mainly of silt and clay layers with interbedded lenses of sand and gravel. The confining unit is not entirely continuous through the study area as depicted in Figure 8. This is most likely due to the heterogeneous character of the low flow conditions giving rise to this fine-grained unit. Although the unit reaches widths of up to 54 m in places near the study area, the layer is on average 8 m with the general thickness staying below 15 m as seen in Figure 9 above. The Lower Aquifer is largely composed of sand and gravel, but it also contains lenses of silt and clay just as the above aquifer does. The average thickness of the confined aquifer is 11 m. Beneath the aquifer and confining units is shale bedrock, which is a unit with a very low hydraulic conductivity.

This study included the analysis of gamma-ray logs and sediment logs collected and provided by the Indiana Geological Survey. The three subdivided units proposed in studies by the USGS are not so well-defined on the local scale of the study area. Upon further inspection, mapping of the logs taken from wells across the study area (Figure 1) showed a miscellaneous layering of variation in grain sizes and degree of lithification. The shallow geology proved to be a complex mosaic of glacial outwash and other interbedded glacial deposits. Across the study area, little to no distinct pattern of layering was indicated by the gamma-ray logs or sediment bore logs.

Hydrogeologic Properties

The potential of the Upper and Lower Aquifers to supply groundwater to wells depends upon their hydraulic properties. The USGS determined the hydraulic conductivity of the various units with a larger region that includes the study area. Estimates were based on two different approaches (Arihood et al., 1998). This first involved collecting data from rudimentary pumping-tests performed on wells following their installation. This method yielded estimates of horizontal hydraulic conductivity at 40 different sites. The simple iterative approach utilized drawdown, pumping-rate and time data and estimated storativity values to calculate the horizontal hydraulic conductivity of both the Upper and Lower Aquifer units. Although the two aquifer units subdivided by the USGS differ in relative composition, the initial well tests found the Lower Aquifer unit to be somewhat more permeable than the Upper Aquifer unit. The median pumping rate was 25 L/s and the average duration for each test was 6.4 hours. From the pump-test data, the overall median horizontal hydraulic conductivity was 0.5×10^{-3} cm/s (Arihood et al., 1998). This value is expected for a largely sand and gravel aquifer that supplies water relatively easily.

Calculation of the median hydraulic conductivity for the units does not imply that the aquifers were homogeneous. Indeed there is large variability in the hydraulic conductivity calculations (Arihood et al., 1998). The aquifers are evidently heterogeneous in composition as reflected by the pump-test data. Due to the inherent variability, the hydraulic conductivity values were somewhat arbitrarily grouped by depth, with 0 to 30 m being the Upper Aquifer and 30 to 60 m being the Lower Aquifer. This grouping scheme also included proximity to the St. Joseph and Elkhart rivers as a variable. The median hydraulic conductivity for the Upper Aquifer was calculated as 0.6×10^{-3} cm/s in locations near the major rivers (Arihood et al., 1998). The proximity of the study area to the St. Joseph River provides a likely generalization of this conductivity for the Upper Aquifer in said location.

Similar calculations and analyses were performed with the Lower Confined aquifer unit. The median hydraulic conductivity for the Lower Aquifer was 1.3×10^{-3} cm/s (Arihood et al., 1998). The higher hydraulic conductivity indicates a somewhat higher hydraulic conductivity for the Lower Aquifer unit. This value was relatively consistent across all areas of the Lower Aquifer regardless of proximity to the river.

The second technique used to provide estimates of hydraulic conductivity came from a trial and error calibration of a groundwater flow model. This approach made use of the hydraulic conductivity measurements noted above and actual water-level measurements. The calibration of said model required a system of continually adjusting variables until the model-simulated characteristics of ground-water levels and discharge matched those measured in the field (Arihood et al., 1998). Comparison values were collected during both dry and wet seasons over a span of 9 years. This method of guess and check created a model that very closely matches the results calculated from raw well data. The parameters that were changed to create an accurate model can be found in Table 2. Data from the pump-test calculations were verified through the second method of calculation: using models. The model-derived horizontal hydraulic conductivities did not differ greatly from those calculated through the Theis Equation from well data.

Table 2. Model Parameters and associated values used for calibration (Arihood, et al. 1998).

Parameter	Calibrated values used in Current Study	Calibrated values used in Imbrigiotta and Martin (1981)
Horizontal Hydraulic conductivity, Upper Aquifer	0.07, 0.6, 1.3 mm/s	0.3—1.4 mm/s
Horizontal Hydraulic conductivity, Lower Aquifer	0.6, 1.3 mm/s	0.3—1.4 mm/s
Vertical Hydraulic conductivity of Confining Unit	$2.5*10^{-4}$ mm/s	$2.5*10^{-4}$ mm/s
Vertical Hydraulic conductivity of streambeds	$3.5*10^{-5}$—0.2 mm/s	$2.5*10^{-4}$—$2.4*10^{-2}$ mm/s

CONTAMINANT HYDROGEOLOGY

Concentration of major contaminants

Rapid industrialization of Elkhart, Indiana led to improper disposal of hazardous chemicals in and around the study area. Large, unsafe plumes of metal, organic cleaning solvents, and other solutes spread across the study area. Of the plumes mapped in Figure 10, two of the five are on the Environmental Protection Agency's list of Superfund sites. The groundwater contaminants vary in chemical structure and concentration depending on the plume of origin. The concentrations of most prevalent and dangerous contaminants are listed in Table 3.

The contaminants listed have been linked to human health effects depending on concentrations. At concentrations of 300 ppb to 500 ppb, trichloroethylene can increase the risk of cancer and having non-cancer health effects such as respiratory effects (ATSDR, 2005). At concentrations greater than 400 ppb, carbon tetrachloride increases risk of kidney and liver damage.

The most prevalent contaminant over all plumes is trichloroethylene (TCE). In the Conrail Railyard Plume, this chemical was detected in more than half of the tested wells with levels up to 4,780 ppb (ATSDR, 2005). Maximum Contamination Level (MCL) set by the United States Environmental Protection Agency (US EPA) is only 5 ppb. TCE measured at three orders of magnitude greater than the MCL causes detrimental health effects including increasing risk of cancer and causing respiratory defects. Conrail is also rich in carbon tetrachloride (CCl_4). Half of the wells tested contained CCl_4 in concentrations up to 6,860ppb (ATSDR, 2005). The MCL for this solvent is 5 ppb. In the LaRue Plume, TCE was in over half of the wells tested, and it occurred in concentrations up to 67 ppb. The second most frequently detected contaminant was trichloroethane (TCA). This chemical was measure in concentrations up to 201 ppb, while the MCL is 5 ppb. CCl_4 was also detected in this plume in a small portion of wells tested with concentrations up to 150ppb. Almost half of the wells tested in the Lusher Avenue Plume contained TCE in concentrations up to 370 ppb. The Gemeinhardt plume contained the metal cleaning solvents TCE and TCA primarily (ATSDR, 2009). Their respective concentrations were not found as shown in Table 3.

Concentrations of hazardous contaminants that are this great pose a large risk to the people of Elkhart, Indiana. Although the concentrations are measured from monitoring wells, they are representative of drinking wells in the area. The contaminants occur in a variety of depths in the groundwater throughout the study area.

Table 3. Summary of groundwater contaminant of concern concentrations according to each plume. All concentrations are listed in parts per billion. All concentrations are measured from monitoring wells, of which most are in the study area. (ATSDR, 2005); (ATSDR, 2009); (EPA, 2014)

Plume	Contamination of Concern	# of Wells containing contaminant	Range of Concentrations (ppb)	Maximum Contaminant Level (ppb)	Wells Above MCL
Conrail Railyard	Dichloroethylene	9 out of 93 tested	ND—60	7	4
	Carbon Tetrachloride	47 out of 94 tested	ND—6,860	5	37
	Trichloroethylene	53 out of 95 tested	ND—4,870	5	41
	Tetrachlorethylene	12 out of 94 tested	ND—2.4	5	0
	Chloroform	1 out of 84 tested	ND—0.8	80	0
	1,1,1-Trichloroethane	2 out of 9 tested	ND—19	200	0
Gemeinhardt	Trischloroethylene and Trichloroethane	—	—	5	—
LaRue	Carbon Tetrachloride	5 out of 64 tested	ND—150	5	3
	Dichloroethane	1 out of 64 tested	ND—17.5	5	1
	Dichloroethylene	6 out of 64 tested	ND—67	7	1
	Trichloroethane	24 out of 64 tested	ND—201	5	8
	Trichloroethylene	43 out of 64 tested	ND—300	5	15
Lusher	Tichloroethylene	41 out of 93 tested	ND—370	5	N/A

Plume Characteristics

The plumes tend to be elongated in the direction parallel to groundwater flow and perpendicular to the river, as seen in Figure 10. Most plumes originate near or in the Conrail Railyard, but not all of them are related through their major contaminants. The river is a terminal boundary for two of the four inspected plumes. It is hypothesized that the contamination plumes from Conrail Railyard and Lusher Avenue (Figure 10) seep into the St. Joseph river along the borders of contact. More research must be conducted, and samples must be collected to make a proper conclusion. The depths of the contaminant plumes were as follows: Lusher Avenue at a depth of 10 to 27 m, LaRue at a depth of 0 to 10 m, and Conrail Railyard at a depth of 10 m down to bedrock at approximately 150 m with most of the groundwater contamination occurring below 27 m. The depth of contaminants in the Gemeinhardt Plume could not be found.

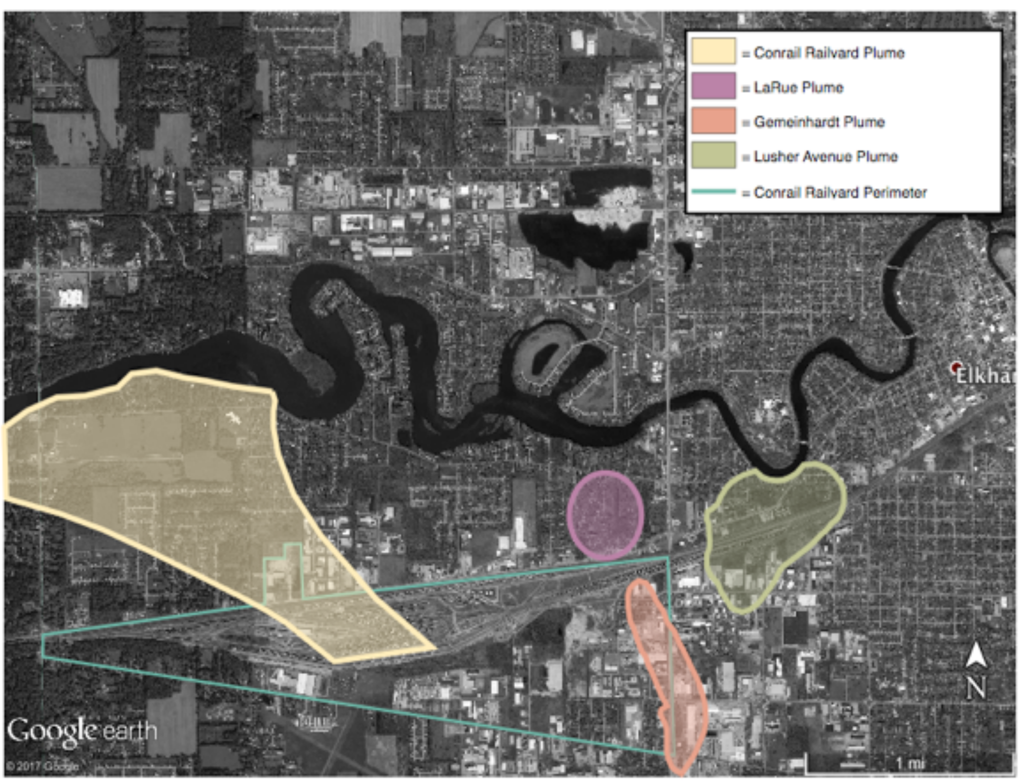

Figure 10. Four notable contamination plumes in Elkhart, Indiana at the study area. Map layer provided by GoogleEarth Pro.

Discussion

Elkhart, Indiana is highly susceptible to groundwater contamination due to the glacial deposits left during the Wisconsin Deglaciation event back in the Pleistocene Epoch. This deglaciation event led to the retreat of three separate lobes of the Laurentide Ice Sheet, creating massive amounts of meltwater. As the deglaciation occurred, deposition in the form of moraines became an important part of the topography in the study area of Elkhart. Another form of glacial deposits from the outwash created a thick and expansive layer of an unlithified mosaic of varying grain size. Unconsolidated stratigraphic units like the one located in the study area promote ample groundwater flow due to the high hydraulic conductivity of the constituents. The extensive reach of glacial meltwater due to retreating glaciers, and the overall flat existing topography of the study area led to the creation of a broad unconfined aquifer. This unconsolidated layer created an ideal aquifer under the city of Elkhart and the surrounding area. The unit beneath Elkhart and other cities in northern Indiana and southern Michigan is relatively rare due to its geographic location in the US Midwest. Due to the unconfined nature and high hydraulic conductivity of this sand and gravel aquifer, contamination risk is high.

Previous studies have shown that there are three distinct stratigraphic units that define the glacial outwash. With an Upper and Lower Aquifer separated by a Confining Unit, most contamination occurring in the unconfined Upper Aquifer would be stopped by the Confining Unit. Analysis of sediment bore logs and gamma-ray logs for the study area indicate that these stratigraphic layers do not appear so neatly. Gaps in the Confining Unit as well as lenses of sand and gravel in this unit promote a more conducive path for groundwater and contaminants to travel. This is most likely the reason for the deep contaminants measured at the Conrail Railyard Plume. The Confining Unit was not complete and most likely contained lenses of material with high hydraulic conductivity that prompted the flow of heavy metal cleaning solvents down to contaminant monitoring wells at depths.

The city of Elkhart started its industrialization in the mid twentieth century, and it has since become one of the most developed areas in Indiana. The booming travel trailer company, music instrument making industry, and rail yard creation caused problems with the groundwater. Creation of metal products requires the use of metal cleaning solvents. These organic, metal cleaning solvents include trichloroethylene, trichloroethane, and carbon tetrachloride. Due to improper disposal of these hazardous contaminants, and the high susceptibility of the unconfined aquifer on the surface, groundwater became contaminated in multiple locations in the study area. The study area itself includes five Superfund Sites according to the Environmental Protection Agency (EPA), two of which (Conrail Railyard and Lusher Avenue) have been mapped. The contaminant plumes cover a large surface area from seemingly small sources. The Gemeinhardt Plume stretches over a mile, but it is formed solely from a one, small storefront, music business. The Lusher Avenue plume is an accumulation of contaminants from multiple small businesses, but it was large enough to become a Superfund Site. The relatively small amount of hazardous cleaning solvents necessary to generate sizable plumes is a characteristic feature of the sand and gravel aquifer units underlying the city of Elkhart.

St. Joseph River has acted as a natural barrier to the further spread of contaminants. All plumes in this study truncate at the river, and this is no coincidence. The solvents flow towards the river with the groundwater due to the localized hydraulic gradient present. No water quality tests were collected in relation to the contaminants in the plumes, so it is unclear if the contaminants have affected the water. Given the hydraulic gradient and porous medium, an interaction between groundwater and surface water is likely to occur. Without the presence of this river, the contaminants most likely would have spread to further extents given the connectivity of the aquifer.

The Upper Aquifer comprising outwash sands and gravels is at risk for contamination from inappropriate disposal of wastes at the ground surface. The relatively large hydraulic conductivity porous, sand and gravel unit coupled with the significant recharge and large topographic gradient has created an active groundwater flow system capable of creating large plumes of dissolved contaminants. More specifically, the proximity to St. Joseph River valley created a local hydraulic gradient, which promoted the rapid spread of contaminants. These factors combined with the high amount of dangerous cleaning solvents used in the industrialized city led to the creation of several significant contaminant plumes.

The city of Elkhart is in the top 25 most populated cities in the state of Indiana. The prevalence of contamination in groundwater poses a health concern for the inhabitants of this location. The cleaning solvents used by industries are dangerous and have been proven to negatively affect human health. With the large surface area and depth variation and the multitude of different contaminants of the plumes, a large portion of the city has most likely been contaminated by this groundwater pollution that occurred in the late 1980s. Studies apart from this one performed by the Agency for Toxic Substances and Disease Registry (ATSDR) show the health effects and estimated exposure to these dangerous chemicals through ingestion of groundwater and inhalation of the volatile organic compounds.

CONCLUSIONS

Widespread glacial outwash deposits led to the vast and thick unconfined aquifer beneath Elkhart Indiana. The aquifer unit, which has been further subdivided into three layers, consists of two aquifers composed mostly of sand and gravel with a silt and clay confining unit. The hydraulic conductivity of the Upper Aquifer is smaller than that of the Lower Aquifer. Groundwater and contaminant flow is faster in the Lower Aquifer, and the groundwater flows in the direction of the river.

The industrialization of Elkhart, Indiana was the root cause of contamination plumes. The highly susceptible, unconfined aquifer became contaminated due to the improper disposal of organic, metal cleaning solvents by many businesses in the city. Characteristics of the aquifer mentioned previously were at fault for the creation of large and hazardous plumes, and the porous and highly connected aquifer allowed for ample travel of contaminants. The St. Joseph river acts as a terminal boundary for the contamination plumes in the study.

Chemical concentrations measured in the four major plumes investigated in the study were high enough to cause damage to human health. Measurements of TCE and CCl_4 concentrations indicated increased risk of respiratory problems, liver and kidney damage, and cancer. When found together, the effects of the contaminants are amplified.

Recommendations for Future Work

The research in this study was limited by the sources available. In order to test if the contaminants effect the chemistry of the St. Joseph River, water samples must be collected, and more field work must be performed. This study only characterized four contamination plumes. Currently, at least three more contamination plumes exist in or near the study area. In the future, these plumes could be added to the plumes that have already been mapped in this study to investigate any overlapping behavior of the plumes. This study only covered a small surface area, while the entire Elkhart County in Indiana has contamination prevalent in the groundwater. On a broader scale, the effects of urban groundwater contamination compared to rural groundwater contamination could be tested. The farmland surrounding the city of Elkhart has many of the same potentially confounding variables as the urbanized portion of Elkhart, making it an ideal location for a comparison study.

The results found through the current study can be applied to other areas of similar geologic history to allow for a better understanding of the aquifer system. The susceptibility of the heterogeneous, unconfined aquifer unit lead to great contamination in Elkhart. If a location with a similar hydrogeological setting has not yet become urbanized and contaminated in the same way, then preventative measures can be put in place to protect the groundwater and the people. Proper disposal techniques could be implemented. Even if the contaminants are not the same, the procedure of placing monitoring wells in highly polluted areas such as in Elkhart could become more widespread.

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